The use of laser scanning as a method for measuring stairways following an accident

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Stairs present significant potential for harm to their users. A fall on stairs, particularly in descent, often leads to serious injury or even death. The authors have been involved in the investigation of many workplace stair accidents. Proper forensic investigation into the cause of a stair accident has often found the incident to be wholly or partly caused by poor stair design. In order to establish the relationship between the stair design and a given fall, an onsite survey has to be conducted, determining the rises and goings along with other key dimensions. The Health and Safety Laboratory (HSL), Buxton, UK, regularly undertake this type of survey using a digital inclinometer, a steel rule and a tape measure. Laser scanning is an emerging technique that is now accessible to the surveyor to complement or replace traditional approaches. The laser scanner and associated software produces a dense point survey in 3D, allowing dimensional analysis of the features. The authors used both traditional and laser scanning techniques to study the scenes of two fatal stair falls. The analysis presented allows the suitability of laser scanning for stair-fall investigation to be considered. Identification and classification of errors are needed in order to consider if the error is acceptable or can be mitigated. Laser scanners are impressive instruments providing data from which can be used to create a virtual 3D environment that can be used to reconstruct and explain an event and contributing factors. The use of both survey methods currently provides the investigator with complimentary data that allows accurate measurements to be presented in the context of the three-dimensional environment.

Keywords: Laser scanning, Stair measurement, Accident investigation, Point cloud data

Importance of effective stair design

Stairs present significant potential for harm to their users. A fall on stairs, particularly in descent, often leads to serious injury or even death. 'A fall on stairs occurs in the UK every 90 s' (BSi, 2010) and in domestic premises there are over 500 deaths per year because of falling down stairs.

The authors have been involved in the investigation of many workplace stair accidents. Further stair accident investigations have come to light anecdotally where a cursory investigation has revealed no obvious damage to the stair or loose component and so in those cases the investigator has concluded that the fall was entirely the fault of the pedestrian. Proper forensic investigations into the causes of stair accidents have often found the incident to be wholly or partly caused by poor stair design.

Below are definitions of common stair terminology (Fig. 1)

- Nosing: the leading edge of the tread. Some stairs will have material added to the leading edge, usually to add visual contrast, protect the edge from wear or provide enhanced slip resistance. This is known as a proprietary nosing.
- Rise: the vertical distance between two consecutive treads, or between a tread and a landing.
- Going: the horizontal distance between two consecutive nosings.
- Pitch: the angle between a line joining consecutive nosings and the horizontal.

Stair descent is essentially a series of controlled falls, from one tread to the next. Increasing the vertical distance between each step makes the control of the fall more demanding, and is therefore more likely to lead to an uncontrolled fall. Equally, reducing the size of the step onto which the foot will land also makes the misplacing of the foot more likely. The size of the going will have a significant influence on fall risk, with smaller goings presenting the highest risk of falls.

Consistency of dimensions within a flight of stairs allows the user to subconsciously adapt, placing their feet accordingly and negotiating the stair with little conscious thought. Where significant differences in rise or going are present between adjacent treads, the risk of falls is significantly increased. Variations in rise are more common at the very top or bottom of a flight, often where a prefabricated stair is connected to a landing

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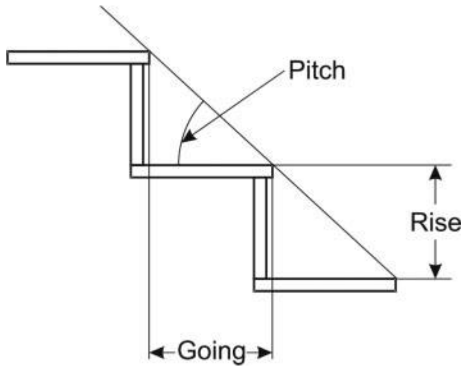


1 Schematic diagram of stair terminology

above or where a floor covering has been added below after a stair has been installed. The effect of variation in going between adjacent treads will be more pronounced on treads with smaller goings.

With respect to the dimensions of goings, the Building Research Establishment (BRE) have published research highlighting the potential risks that can be associated with poor stair design including the effect of changing going dimensions (Roys and Wright, 2003). Table 1 shows the effect of going dimensions and variations between treads on the risk of a large overstep, where action should be considered if the average time between occurrences is 50 years or less (Roys and Wright, 2003).

It can be seen from the table above that a small change in the dimensions within a staircase can have a significant effect on the associated risks in their operation. However, there are also additional factors that affect staircase safety and measures can be derived to mitigate against them. Such as, a clear highlight at the very edge of the tread (the nosing) makes it easier to distinguish precisely where the step ends and improves ability to place the foot correctly and therefore safely negotiate the stair. The highlight should extend across the entire width of the tread, should be a single colour to avoid confusing visual cues and should be of a colour that contrasts clearly with the material of the treads, the floor coverings at the top and bottom of the flight and on any landings. In addition to differences in colour, differences in the light reflectance value (LRV) can help to differentiate a nosing highlight from the tread below. The shape of the nosing is also important. A square nosing gives a clearer impression of where the very edge of the tread is and maximises the possible going of the tread when compared with a curved nosing with a large radius. However, a radius of 6 mm on the nosing is suggested to reduce the severity of injuries sustained during a stair fall.

Handrails serve three main functions: a guide for stair use, an aid to movement on stairs, and a method of preventing a fall. In order to suitably perform these functions, the handrail needs to be appropriately designed. Handrails should follow the pitch of the stair and be graspable and within easy reach over the full length of the stair. Research into the appropriate height for the handrail has led most standards to recommend a height of 900–1000 mm above the pitch line, measured from the nosing to the top of the handrail. Visual identification of a handrail is easier for stair users when the handrail contrasts with the surrounding environment, as discussed in relation to nosings above.

Survey methodology: physical stair measurements

In order to investigate a stair-fall accident, an onsite survey is required to establish the stair characteristics, determining the rises and goings while also examining if the handrails are appropriate. Health and Safety Laboratory (HSL) normally undertake this survey using a calibrated digital inclinometer, steel rule and tape measure. The inclinometer is used to obtain the angle between adjacent nosings with direct reading of 0.1° and the steel rule is used to measure the slope distance (SD) between the nosings of the steps to be measured. The methodology used is inline with the improved method highlighted by Johnson (2006). The measurements for the rise and going for each step can be calculated, in turn using basic trigonometry.

In addition to obtaining the dimensions of the rise and goings of the stairs, measurements of the clear width of the stairs and the location and design of the handrails also have to be taken. Handrails need to be appropriately designed if they are to be used successfully as an

Table 1 Effect of going and variation between treads on the risk of a large overstep (Roys and Wright, 2003)

Going	Average time between occurrences of large overstep			
	5 runs per day	25 runs per day	100 runs per day	2000 runs per day
Risk on a 14-step light where there is no variation in going between steps				
225 mm	4 years	298 days	75 days	4 days
250 mm	11 years	2 years	198 days	10 days
275 mm	145 years	29 years	7 years	133 days
300 mm	>1000 years	>1000 years	>1000 years	73 years
325 mm	>100 000 years	>1000 years	>1000 years	568 years
350 mm	>100,000 years	>100,000 years	>100,000 years	>1000 years
375 mm	>100,000 years	>100,000 years	>100,000 years	>1000 years
400 mm	>100,000 years	>100,000 years	>100,000 years	>100,000 years
Risk on a 14-step flight where a single going is reduced by 10 mm				
225 mm	2 Years	139 days	35 days	2 days
250 mm	5 Years	340 days	85 days	4 days
275 mm	50 years	10 years	53 years	46 days
300 mm	>1000 years	>1000 years	323 years	16 years
325 mm	>100,000 years	>1000 years	>1000 years	105 years
350 mm	>100,000 years	>100,000 years	>100,000 years	>1000 years
375 mm	>100,000 years	>100,000 years	>100,000 years	>1000 years
400 mm	>100,000 years	>100,000 years	>100,000 years	>1000 years

aid to negotiating the stair or to arrest a fall. Measurements of the handrail height are obtained by placing a tape measure on the nosing and extending vertically at two locations. The clearance between the handrail and the wall is measured with the tape measure and the perimeter of the handrail is measured by wrapping a string around the rail and comparing the length of string used with the calibrated rule.

Survey methodology: laser scanning

Over recent years, there have been considerable developments in geospatial equipment and technology. Laser scanners now have the capability to capture up to one million times a second (Leica Geosystems, 2012) generating a dense point cloud. The data obtained using laser scanners can be used in order to produce 2D plans or to build 3D models of the area surveyed.

New and innovative data capture and processing methods are continually being developed, with laser scanning being the survey methodology of choice for a wide range of different applications including accident investigation, in particular road traffic collisions (RTCs) (Pagounis *et al.,* 2006).

On site survey

In order to obtain a 3D survey of a scene, a number of stages have to be undertaken as follows (Quintero *et al.,* 2008):

- Optimal scanner set-up positions, with regard to scene coverage and efficiency
- Full visibility of scene
- Visibility of survey control
- Safety of the surveyor
- The scene is within range of the instrument

When undertaking a survey for stair-fall investigations, it is important to ensure that the laser scanner is carefully levelled before a scan can commence. This can be achieved using the in built inclinometer (HDS6000: dual axis sensor and C10: dual axis compensator), which is essential for precise measurement needed in this application. On many occasions, a scene will require a number of scan set-up locations in order to record the environment in full (i.e. to overcome blind spots or to improve resolution), which are then later combined in software. With this in mind, there needs to be a method of combining the different point clouds. This process is known as registration.

Data processing

There are two principal methods of registration:

- Target registration
- Cloud to cloud registration

Target registration

Targets can be positioned throughout the scene in order to constrain two or more scan locations. The targets locations remain static between scans. However, some targets can be rotated to face the next setup location. This is possible as the targets are designed such that the centre remains constant, irrespective of how it is tilted or rotated. Once recorded, vertexes can be assigned to the centre of the target using specialist software that provides an accurate 3D position. The targets (at least three) then become the constraints between the two laser scans and vertex errors are produced as a result of this operation.

Cloud to cloud registration

Occasionally, the characteristics of a site may not suit the use of targets. For example, if there has been an accident resulting from a major collapse or structural failure and parts of the scene are inaccessible, then the surveyor must consider another option to combine the setup locations. One of the options available is the use of cloud to cloud registration. Common points (at least three) are selected within the two set ups, these points then form the constraints between the locations. The result is an alignment error; this is the maximum mean error between the two locations.

Combination

The two forms of registration can be used in conjunction with each other. Target registration can be used to constrain the scans and cloud to cloud registration used to 'smooth" the result. This is the preferred form of registration and the one used by the authors in the case studies detailed below. However, as with all types of survey sources of error require careful consideration, particularly since the survey could be used in evidence.

Determining the position of handrails

As previously stated, it is important for the accident investigator to obtain information in respect to the construction and suitability of handrails, with the conventional method of measurement discussed. This can also be achieved using a laser scanner using surface fitting algorithms such as the ones found within Leica cyclone. Laser scanning software allows the user to use the point cloud survey to assign 'solid' 3D primitives to the record data to a high degree of accuracy. In many cases, such as the handrails in the Quay Case are cylindrical in shape, therefore cylinders can be fitted to the point cloud to accurately model their location.

In certain cases, it may be important to obtain a profile of the handrail for assessment. This can be achieved by clipping (showing only a selection of the point cloud) the area of the point cloud that is required and showing it in profile, which can be evaluated to establish if it is fit for purpose. In addition, small sections can be taken at any location along the handrail, allowing the investigator to evaluate the handrail in full.

Taking stair measurements from laser scan data

In order to obtain measurements for the rise and goings of stairs, there are a number of stages that have to be undertaken:

- separation of staircase from the complete survey;
- establishing a user coordinate system (UCS);
- taking measurements and presenting the data.

Separation of staircase from the complete survey

When laser scanning a scene, the associated dataset can be considerable particularly if a number of set-up locations are required. Subsequently, the surveyed environment may include information that may be of relevance for the overall investigation process or context, but having seemingly no significance to the staircase itself. With this in mind, the staircase may be separated from the complete scene for further examination. It is important at this point to copy the dataset to preserve the original that may be required at a later date for other purposes; following this, the staircase can be extracted for further examination. In addition, as large point clouds require considerable computing power to display; by extracting the required data, it allows the computer to operate more efficiently and display the selected object in more detail.

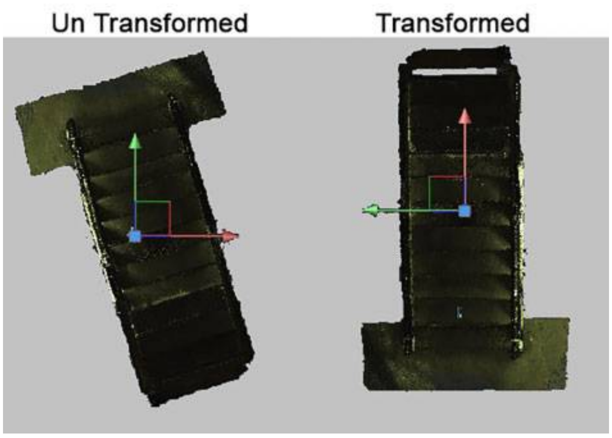
Establishing a user coordinate system (UCS)

The purpose of creating a UCS in this way is to create a local coordinate system that is aligned with the stair itself and not determined by the orientation of the laser scanner from its first position. The UCS will then establish views, which are directly proportional to the staircase, i.e. right or left views representing the stairs 'side on'. This can be achieved in a number of ways within point cloud processing software. One of the steps can be selected and the 'y axis' aligned to the tread of the step, the 'x axis' is then determined at a 90° angle following the path of the stair string (an effective UCS can also be achieved by reversing this operation). Finally, the 'z axis" will be directly vertical from the x–y plane. An example of the survey uncorrected and set to a UCS is shown in Fig. 2.

Taking measurements and presenting the data

When a UCS has been set relative to the direction of the stairs, measurements can then be taken from the data. However, before this can be undertaken a section through the data has to be obtained relevant to where the measurements are required. For example, if the staircase has received a high amount of traffic the centre of the stair could be worn, therefore it may be relevant to take sections and subsequent measurements from the centre and also the edges of the staircase. A section was taken through the point cloud to ensure that the measurements were taken from the same location as the ones obtained by conventional means. In addition, this methodology was chosen over fitting surfaces to the cloud as surfaces would not represent the wear that may have occurred on the edge of the nosing. However, fitting surfaces would reduce the effect of noise that is often created when using a laser scanner. Therefore, in order to compensate for mismeasurement that could occur by taking a reading from noise in the point cloud, this process is then repeated a number of times through a small section of data.

Once a section has been taken through the data within a CAD drafting package, the staircase can be viewed from the side and measurements for the angle and distance between adjacent nosings can be determined. As the placement for the point of measurement is subjective, this can be undertaken a number of times in order to obtain a spectrum of results and reduce the propagation of error, upon application of an arithmetic mean and standard derivation can be applied. The data can also be plotted and displayed to scale, an example of which is shown below in Fig. 3.



2 User Coordinate System (UCS) configuration

Case study 1: quay, fatal accident

Background of the incident

An elderly lady died after she fell from quayside steps into the river below. She had been disembarking a passenger ferry beside a quay when the fall occurred. The authors were asked to examine the steps as part of the investigation process and were called as expert witnesses in the trial. The HSL were contacted by Health & Safety Executive (HSE) to undertake a stair-fall assessment. This included physical measurements of the dimensions to determine the relative rises and goings. In addition, a laser scan survey was carried out, using a Leica HDS6000 laser scanner and high definition camera assembly, to record the scene retrospectively of the incident. The survey was used to highlight the changes that were made to the steps to reduce any further risk associated with their use, following recommendations from HSL.

Results

The results for the physical measured survey and laser scan survey are shown in Table 2, with the measurements taken from the edge of the stair on the nosing.

A comparison between the two surveys is shown in Table 3.

It can be seen from the table that there are differences between the two sets of data with a maximum deviation of 5 mm. There are a number of possible variables that may have had an effect on this. These are highlighted in Section 6.

Case study 2: cellar stair, fatal accident

Background of the incident

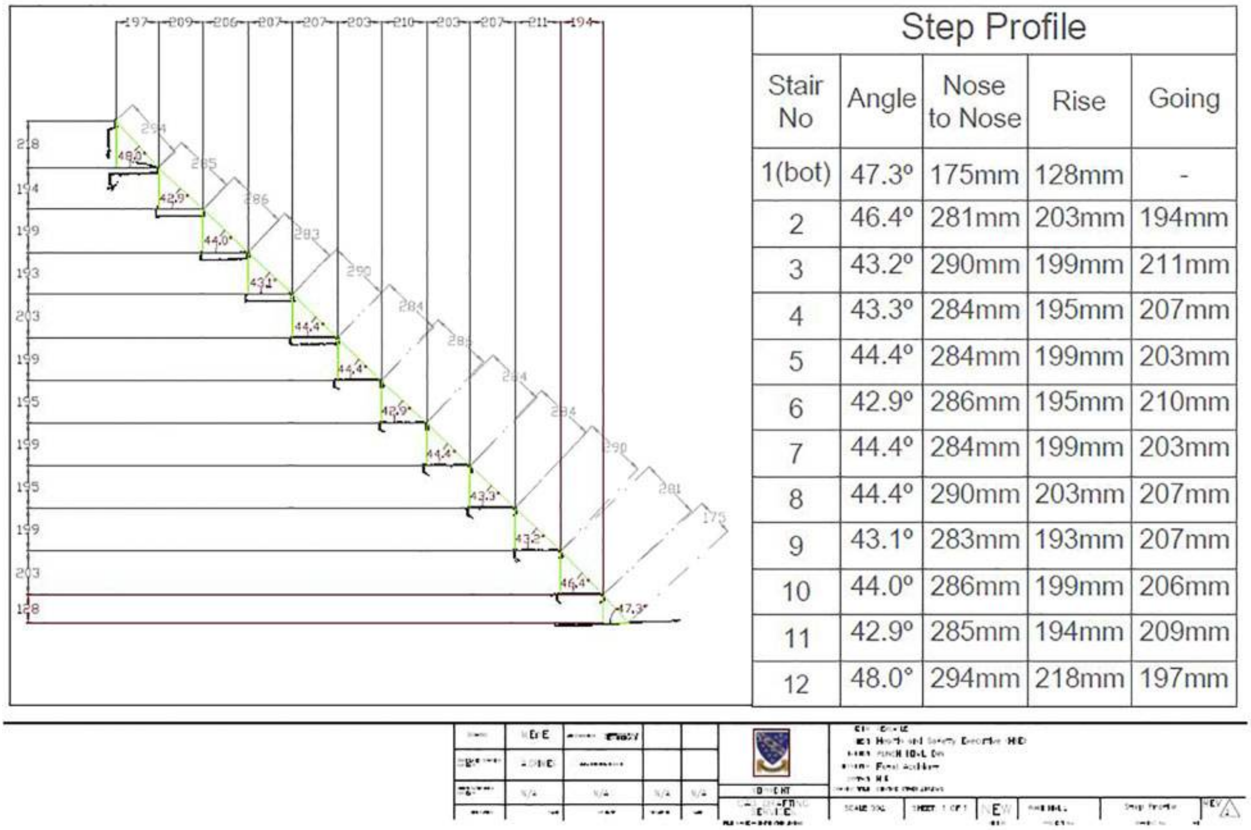
During 2012, a male publican died after falling on the stairs leading down to the beer cellar in his public house.

The authors were asked to examine the steps as part of the investigation process. Health and Safety Laboratory were contacted by the Environmental Health Department at the Local Authority to undertake a stair-fall assessment. This included physical measurements of the dimensions to determine the relative rises and goings. In addition, a laser scan survey was carried out, using a Leica C10, to record the scene of the incident.

The business was served with an Improvement Notice, which required a number of changes to reduce the risk of future stair-falls. The notice was complied with by way of installing a new flight of stairs and improved lighting in the area, at the company's cost.

Results

Within this case study, the staircase was subject to wear in the centre because of heavy footfall. With this in mind, the measurements in this section were taken from a number of positions in order to evaluate the wear. In order to better understand the measurement locations, a schematic has been produced and is shown in Fig. 4, showing a profile through a step and the location in which a measurement was taken.



Step Profile				
Stair No	Angle	Nose to Nose	Rise	Going
1(bot)	47.3º	175mm	128mm	-
2	46.4º	281mm	203mm	194mm
3	43.2º	290mm	199mm	211mm
4	43.3º	284mm	195mm	207mm
5	44.4º	284mm	199mm	203mm
6	42.9º	286mm	195mm	210mm
7	44.4º	284mm	199mm	203mm
8	44.4º	290mm	203mm	207mm
9	43.1º	283mm	193mm	207mm
10	44.0º	286mm	199mm	206mm
11	42.9º	285mm	194mm	209mm
12	48.0°	294mm	218mm	197mm

3 Presentation of results

Table 2 Results of physical measured survey and laser scan survey

Stair number	Angle (°) PS	Angle (°) LS	SD (mm) PS	SD (mm) LS	Rise (mm) PS	Rise (mm) LS	Going (mm) PS	Going (mm) LS
1 (Bot)	–	27.8	–	619	302	302	299	303
2	28.4	28.4	340	345	162	164	262	264
3	31.5	31.9	307	311	160	164	255	252
4	33.3	33.5	305	302	167	167	258	256
5	32.5	32.8	306	304	164	165	258	260
6	31.2	31.2	302	304	156	157	291	286
7	28.2	29.1	330	327	156	159	–	–
Min	28.2	27.8	302	302	156	157	255	252
Max	33.3	33.5	340	619	302	302	299	303
Mean	30.9	30.7	315	376	191	192	268	269

PS: physical measured survey; LS: laser scan survey.

Table 3 Difference between the two surveys

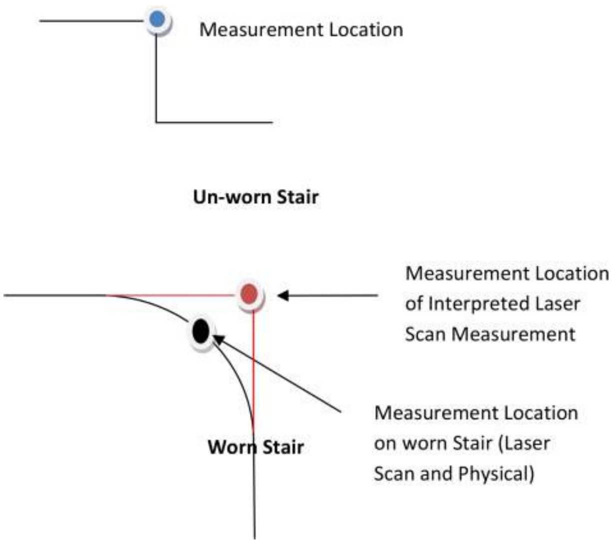
Stair Number	Angle diff (°)	SD diff (mm)	Rise diff (mm)	Going diff (mm)
1	−0.9	3	−3	
2	0.0	−2	−1	5
3	−0.3	2	0	−2
4	−0.2	3	1	3
5	−0.4	−4	−4	3
6	0.0	−5	−2	−2
7			0	−4
Max	0.0	3	1	5
Min	−0.9	−5	−4	−4
Error ±	1.0	5	4	5

There was considerable wear from heavy footfall to the centre of the stair. For this reason in this case study, physical measurements were taken from the centre of the stair on the point of wear (black circle in Fig. 4). The measurements of the physical survey and laser scan from the centre stair are shown in Table 4.

A comparison of these two datasets is shown in Table 5, which shows discrepancies between the data with differences of 10 mm in the rises and 13 mm in the goings. This is considerable considering the narrow margin of error that triggers action within the building regulations governing stair design. There are a number of possible sources of error that have to be considered, these are highlighted later in Section 6.

As the stairs were worn in the middle because of high footfall, measurements were taken on the edge of the stair string to compensate for this in both the physical and laser scan survey (blue circle in Fig. 4). The results for the two surveys are shown in Table 6.

A comparison between the two sets of measurements is shown in Table 7 with considerable differences between the



4 Schematic of measurement locations

datasets including a maximum error of 24 mm. In order to evaluate this error, first it must be classified.

One of the benefits of capturing a scene using a laser scanner is the ability to examine the staircase any number of times and applying different techniques. Using the section through the laser scan at the centre of the staircase, an extrapolated value for an unworn nosing (red circle in Fig. 4) was taken to compensate for wear and the results are shown in Table 8.

The measurements were then compared to the physical measurements taken to one side (blue circle in Fig. 4), as shown in Table 6 to identify a possible correlation.

The comparison results are shown in Table 9, which identifies differences between these data sets, further examination is required in order to establish if this is error or the result of inherent differences within the staircase. For example, there may be a dip within the stair tread at the centre of the stair, which has resulted in the differences shown.

Sources of error

As with all forms of survey, measurements are susceptible to some form of error.

Errors from undertaking a physical survey

There are a number of sources of error that occur when undertaking a physical survey using the improved method described by Johnson, which are listed below:

- Inclinometer instrument error
- Rule miss read and booking errors
- Rule and inclinometer misplacement
- Temperature
- Sectional measurement alignment

Sources of error using a laser scanner

There are a number of key sources of error when using a laser scanner. These are highlighted below with reference to the two case studies:

- Errors in registration
- Instrument errors
- Surface errors
- Environmental errors
- Resolution
- Interpretation
- Setting of UCS

Contributing error

As there are a number of variables sources of error between the two surveys, and the comparison has been performed retrospectively, the contributing error is hard to establish. Further work is required in order to quantify the specific error, with the importance placed on accuracy and repeatability to assess the possibility of using a laser scanner as part of a stair-fall assessment.

Benefits of using a laser scanner

There are a number of key benefits to using laser scan technology to evaluate a stairs construction.

Obtaining the bottom step angle

When undertaking a survey and taking measurements physically, it can be problematic obtaining the angle for the bottom step. This occurs because there is not another nosing for the inclinometer to be placed on, therefore the final rise is normally measured using traditionally from the floor to the tip of the nosing. However, this can be a cause of error if the ground is uneven or sloping and the measurement does not reflect the actual rise.

Table 4 Physical measurements and laser scan survey taken from the centre stair

Stair Number	Angle (°) PS	Angle (°) LS	SD (mm) PS	SD (mm) LS	Rise (mm) PS	Rise (mm) LS	Going (mm) PS	Going (mm) LS
1 (Bot)		47.3		175	140	128	181	194
2	47.8	46.4	270	281	200	203	208	211
3	44.2	43.2	290	290	202	199	198	207
4	44.9	43.3	280	284	198	195	196	203
5	45.6	44.4	280	284	200	199	208	210
6	44.3	42.9	290	286	203	195	197	203
7	45.4	44.4	280	284	199	199	203	207
8	45.6	44.4	290	290	207	203	201	207
9	44	43.1	280	283	195	193	203	206
10	45.6	44	290	286	207	199	206	209
11	44.7	42.9	290	285	204	194	187	197
12	49.1	48	285	294	215	218		
Max	49.1	48	290	294	215	218	208	211
Min	44	42.9	270	175	140	128	181	194
Mean	45.6	44.5	284	277	198	194	199	205
Range					75	90	27	17

PS: physical measured survey; LS: laser scan survey.

Table 5 Comparison of worn centre stair measurements

Difference	Angle (°)	SD mm)	Rise (mm)	Going (mm)
1			12	–
2	1.4	−11	−3	−13
3	1.0	0	3	−3
4	1.6	−4	3	−9
5	1.2	−4	1	−7
6	1.4	4	−8	−2
7	1.0	−4	0	−6
8	1.2	0	4	−4
9	0.9	−3	2	−6
10	1.6	4	8	−3
11	1.8	5	10	−3
12	1.1	−9	−3	−10
Max	1.8	5	10	−2
Min	0.9	−11	−3	−13
Error ±	1.8	11	10	13

The bottom angle can be obtained from taking the measurement using laser scan data. A virtual nosing can be projected from the bottom step nosing at a difference equal to the average going of the flight. This can be used to calculate the first rise using Johnsons approved method stated previously.

Obtaining the handrail in 3D

Having a 3D model of the handrail can be beneficial when assessing its suitability, as the cross-section of the rail can be examined. An accurate measurement for the diameter for the whole rail can also be determined as explained previously.

In addition, the positions for the stanchions can be obtained at the base and top. This can be hard to obtain through conventional means if the stanchion is not upright. In addition, the layout of all handrails can be shown in 3D and the positions shown relative to all other objects in the scene in a way that is easy to understand.

Data clarity

If a staircase has been found to have dimensional inconsistencies, alterations to the rises and goings may need to be made to make the stair safer. This is typically done by producing a 2D representation of the changes in which a tradesman will use when making changes. The use of a 3D model can be of considerable benefit in the explanation of the changes, particularly if the required alterations are complex.

Repeatability of measurements

In order to reduce propagation of error it is necessary to undertake measurements a number of times. If the environment has been laser scanned repeat measurements can be taken quickly once the UCS has been obtained. This is considerably quicker than taking rounds of measurements in the field.

Multiple uses for the data obtained

As the dataset obtained using a laser scanner is very rich, it can be used for a multiple of different applications within the accident investigation process. Examples include recording the scene, testing hypotheses and allowing for incident reconstruction. In addition, if a scene that has already been laser scanned, the existing data can be used to evaluate the stair virtually, without sending an expert to the scene, which can have implications in terms of cost and safety.

Safety

Undertaking a physical survey, particularly on a stair where an incident has occurred, may put an expert at risk of falling. Most modern laser scanners have the ability to be operated remotely via an internet connection and have various ranges of non-contact measurement (in the extreme, up to 6 km). Considering this, if the environment is captured using a laser scanner, and the evaluation of the staircase performed remotely, this will drastically reduce the exposure to the hazard.

Education

Once laser scanned, the scene is recorded digitally and can be archived and referenced at any point in time, if required. One particular use for the data could be to educate people on the potential hazards and consequences of poor stair design and the implications this may have. A geodetic and visually accurate 3D scene derived using laser scanning technology can be used to recreate and reenact possible scenarios and demonstrate good practice, thereby helping to prevent further accidents.

Table 6 Measurements taken at the side of the staircase

Stair number	Angle (°) PS	Angle (°)Ls	SD (mm) PS	SD (mm) LS	Rise (mm) PS	Rise (mm) LS	Going (mm) PS	Going (mm) LS
1 (Bot)		49.4		172	136	131		112
2	47.4	45.8	284	287	209	206	192	200
3	44.5	43.9	289	286	203	198	206	206
4	45	43.9	284	284	201	197	201	205
5	46.3	45	280	280	202	198	193	198
6	43.9	42.7	295	294	205	199	213	216
7	45.5	44.3	283	284	202	198	198	203
8	44.9	43.5	288	288	203	198	204	209
9	45.6	44.7	283	283	202	199	196	201
10	45	43.5	287	290	203	200	203	210
11	45.4	43.7	285	281	203	194	200	203
12	48	47.1	293	299	218	219	196	204
Max	48	47.1	295	299	218	219	213	216
Min	43.9	42.7	280	172	136	131	192	112
Mean	45.6	44.8	286	277	199	195	200	197
Range					82	88	21	104

PS: physical measured survey; LS: laser scan survey.

Table 7 Comparison between measurements taken at the side

Difference	Angle (°)	SD (mm)	Rise (mm)	Going (mm)
1			−24	
2	−1.6	3	−9	14
3	−0.6	−3	3	−8
4	−1.1	0	4	−4
5	−1.3	0	−4	5
6	−1.2	−1	11	−14
7	−1.2	1	1	0
8	−1.4	0	6	−6
9	−0.9	0	−1	1
10	−1.5	3	7	−3
11	−1.7	−4	0	−6
12	−0.9	6	−14	23
Max	−0.6	6	11	23
Min	−1.7	−4	−24	−14
Error Neg and Pos	2.6	6	24	23

Table 8 Measurements taken compensating for wear

Nosing (to...)	Angle (°)	SD (mm)	Rise (mm)	Going (mm)
1	43.4	192	140	132
2	45.8	283	197	203
3	43	292	214	199
4	43.7	283	205	196
5	44.2	283	203	197
6	43.1	288	210	197
7	44.5	283	202	198
8	43.6	290	210	200
9	43.5	281	204	193
10	44.6	288	205	202
11	42.4	285	210	192
12	47.9	294	197	218
		Max	214	218
		Min	140	132
		Average	200	194
		Range	74	86

Table 9 Comparison between measurements to the side to interpreted wear

Difference	Angle (°)	SD (mm)	Rise (mm)	Going (mm)
1	–	–	4	–
2	−1.6	−1	12	11
3	−1.5	3	11	−7
4	−1.3	−1	4	−5
5	−2.1	3	1	4
6	−0.8	−7	5	−16
7	−1	0	0	0
8	−1.3	2	7	−4
9	−2.1	−2	2	−5
10	−0.4	1	2	−1
11	−3	0	7	−8
12	−0.1	1	−21	22
Max	−0.1	3	11	22
Min	−3.0	−7	−21	−16
Error Neg and Pos	3.0	7	21	16

Multiple sections

By using a laser scanner to survey the stair and record the full environment, multiple sections can be created and used for stair measurements. This could provide the ability to compensate for deviations in the step profile between the stair strings. In performing multiple sections across the stair tread, a range of results can be obtained, providing a greater number of readings to be assessed. This also has additional benefits if one section through the stairs is damaged and others are not.

Calculation of wear

Using the laser scan data, the rises and the goings can be extended virtually and the point in which they intersect represents the stair with 'no wear'. This is of particular importance if a survey is performed on stairs that have received a high footfall and the measurement is taken from the area of highest traffic.

Speed and density of data

A laser scanner provides a density of data that is unprecedented to conventional survey techniques in a short period of time, creating a geodetic and visually accurate 3D environment (if digitally imagery is incorporated in the survey methodology). The associated dataset can then be used as a base to best fit surfaces upon to create a virtual 3D model such as the one shown in Fig. 5. Such models are useful to evaluate the incident and explain the environment to others in a way that is easy to comprehend.

Limitations of using a laser scanner

Adopting laser scanning technology for the use in the assessment of stair construction is not without its limitations.

Interpretation

When undertaking staircase measurements using a laser scanner, it is important to limit possible sources of error in the dataset. The point, which is measured within the drafting package (where the curser is placed), is subjective and is at the discretion of the user. As the point cloud is made up of millions of points, it is hard to determine which point is exact to record. Therefore, in order to reduce this possible source of error, multiple rounds of measurements should be taken, an arithmetic mean taken and standard deviation used to reduce any propagation of error.

Cost

Laser scanning technology is still relatively new, with the equipment and related software expensive as a result. With this in mind, the use of laser scanners may not be appropriate for every incident. However, as the technology matures, the costs related with its use will reduce making it a more sustainable solution for accident investigation.

Errors using laser scanning systems

There are a number of sources of error that can be incorporated into a laser scan survey that have been highlighted previously. The sources of error have to be controlled where possible, with the survey carried out inline with best practice. Therefore, taking multiple rounds of measurement, ensuring the equipment is in calibration and appropriate for the selected task. As there are limited tolerances in the deviation in stair design governed by building regulations, it is essential to

5 An example of a model that has been created using best fit surfaces

understand and reduce these variable sources of error highlighted previously.

Conclusions

The purpose of this paper was to explore the possibility of using a laser scanner for assessing key stair dimensions and it can be seen from the two case studies presented that measurements can be made using a laser scanner.

While incorporating this technology into a stair-fall assessment can provide a wide range of benefits with regards to safety and the explanation of the environment to people other than the investigator, further work is required to assess the effect of the various sources of error that have been explored within this paper. With the lack of a population of measurements on the physical survey, it is hard to statistically assess the accuracy of the measured results to categorically state that the laser scanner is responsible for most of the contributing error, although the authors believe this to be the case.

Laser scanners are impressive instruments to recreate an as-built virtual 3D environment that can be used in the explanation of the event, contributing factors and incident reconstruction. In addition, the recorded data can be used to address leading factors (through simulation of incidents in an geodetically accurate environment) and educate people in the implication of defective stair design. Therefore, deploying a laser scanner to survey accident scenes has considerable benefits that cannot be achieved through conventional means, where the data obtained can be used for a magnitude of different applications.

Owing to the errors associated with laser scanners, for precise high accuracy surveys to narrow tolerances such as the measurements of rise and goings outlined in this paper, laser scanning may not be the best survey methodology available. For example, the use of conventional levelling may be used to obtain the measurements for the rise of a stair to a very high tolerance. In addition, in many cases the justification for a survey using a laser scanner may not be warranted within an accident investigation with regard to cost, availability of equipment and the processing of the associated dataset obtained. However, the classification of the error from laser scanning must be established, in order to consider if the error is relative and therefore can be mitigated, through further research. In addition, the authors plan to explore the use of different laser scanning systems that may be better suited to the task of stair measurement.

The advancement in laser scanning technology has been phenomenal and, although currently within its infancy, new and innovative applications are continually being developed. This means that there are exciting times ahead within the industry and improvements in the equipment will ultimately result in laser scanners being the equipment of choice for many survey applications. With the advancements already achieved in a relatively small life cycle have been amazing, providing the geospatial industry information that previously could not be imagined making the real world virtual.

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